Steady-state auditory evoked fields to multiple amplitude modulated tones

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1 Introduction

Amplitude modulations (AM) are important and characteristic feature of complex sounds like speech and music. Different modulation frequencies produce different types of perceptions (fluctuation strength, roughness or pitch). AM tones with modulation frequencies of about 40 Hz are mostly used to elicit steady-state responses (SSR) [6]. In a recent MEG study, the SSR of modulation frequencies in the range from 10 to 80 Hz were demonstrated [7]. Combinations of AM signals with different carrier and modulation frequencies were used in order to investigate the dependency of amplitude and phase of SSR on the stimulus parameters [2]. In this study however, multiple amplitude modulated stimuli with a single carrier frequency are used, in order to investigate the parallel processing and coding of different perceptions at the level of the human auditory cortex. Such a stimulation eliciting simultaneously different types of responses in dependence on the temporal structure of the stimulus could be implicated in studying of central auditory disorders [1].

2 Methods

2.1 Subjects

Nine subjects (7 male and 2 female) between the ages of 24 and 34 years participated in this study. Informal consent was obtained from all subjects after explaining the aim of the study in accordance with the Ethic Comission of the University of Münster and the Declaration of Helsinki.

2.2 Stimulation

The temporal structure of the stimulus signal, shown in Fig. 1(bottom) was a sinusoidal tone of 250 Hz as carrier frequency, which was modulated with a sum of two sinusoidal modulation frequencies of 38 and 40 Hz. The modulation depth was set to 1. This stimulus was continuously presented to the subjects right ear for a period of 200 s. The amplitude spectrum of the stimulus is demonstrated in Fig. 1(top). The interference of the modulation signals resulted in a 2 Hz beat rhythm, which was clearly perceivable but with no contribution to the stimulus spectrum. Intensity of the stimulus was set to 70 dB$_{SL}$.

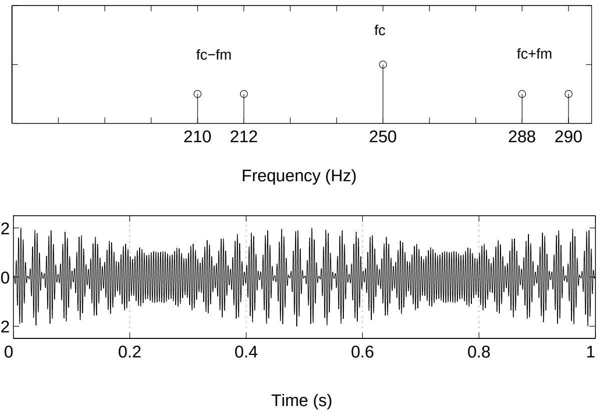

Figure 1: *Amplitude spectrum and temporal profile of the stimulus*

2.3 Data acquisition

Recordings were carried out in a magnetically and acoustically shielded room using a 37-channel biomagnetometer (MAGNES, Biomagnetic Technologies). The sensor array was placed above the auditory cortex contralateral to the stimulated right ear. The complex AM stimulation was used, continuously presented in 14 repeating runs, each one with duration of 200 s, within an experimental session of 1.5 hour. The data were bandpassed between 1 and 200 Hz and sampled at a rate of 520 Hz.

2.4 Data analysis

The data stream of each run was averaged in time domain within a period of 4 seconds. This time window was split into 1 seconds subintervals, related to the trigger. The averaging procedure was performed by shifting of the time window with a step equal to the length of the subinterval, i.e. 1 second. Segments with amplitude fluctuation more than 3 pT were considered as artifact contaminated and were rejected. The averaged data were then low-pass filtered with a second order zero-phase shift Butterworth filter within the frequency range from 1 to 24 Hz. The resulting 37 magnetic fields waveforms were averaged across all 14 runs and referred as low-frequency response (LFR). The same procedure was performed for the high frequency range (24 to 100 Hz) and the resulting waveform was referred as high frequency response (HFR). Subsequent sections of length equal to one period of the modulation frequencies 38 and 40 Hz were averaged, forming the response time series for these modulation frequencies.

Source analysis using the model of moving equivalent current dipole (ECD) in a sphere was used and (x, y, z)-coordinates of source location at the time of maximum of the field power and dipole moment were estimated. Only those values were included which were in agreement with following anatomical and statistical requirements: distance from the midsaggital plane greater than 3.5 cm, and goodness of fit of the dipolar source >90%. The median value of source coordinates and orientations of the LFR and HFR were estimated and used as a reference for the applied source-space projection method.

This method was used in order to obtain the source waveform of the steady-state response. It estimates the activity in a certain brain area by linear combination of activities measured outside the brain and collapses the time series of the 37 MEG sensors into a single-channel signal. Finally, a grand average across all subjects was calculated.

A Fourier transform was applied to the time series of the obtained source waveform, consisting of 2048 samples in a length of approximately 4 s.

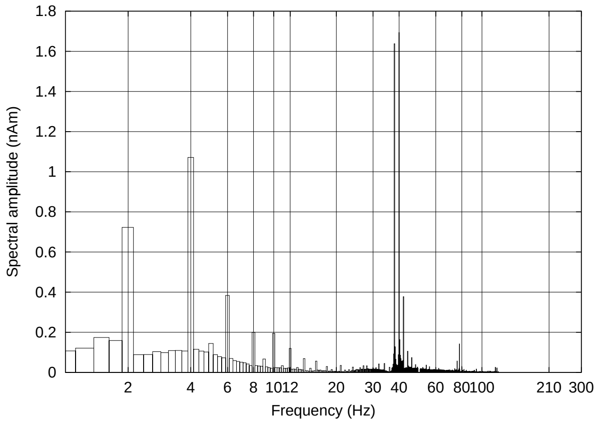

Figure 2: *Grand average amplitude spectrum across 9 subjects, shows groups of components below 20 Hz (LFR) and around 40 Hz (HFR).*

The spectrum was shown upon logarithmic frequency scale ranged from 0 to 300 Hz, with a resolution of 0.25 Hz. Grand average spectrum across all subjects was calculated using real and imaginary Fourier spectral coefficients.

3 Results

3.1 Frequency spectrum

The grand average amplitude spectrum of the response is shown in Fig. 2. Pronounced spectral lines around 40 Hz and below 20 Hz can be seen. The two frequency ranges are clearly separated. The low frequency spectrum was characterized by peaks at 2, 4, 6 Hz etc. Within the high frequency range, the peaks at both modulation frequencies of 38 and 40 Hz were with highest amplitudes.

3.2 Time domain

The time series of LFR and HFR of individual subject are illustrated in Fig. 3. Both responses have similarly pronounced dipolar distribution.
The time course of the stimulus signal and the dipole moment amplitude of LFR and HFR are presented in Fig. 4. The rhythmic change between modulated (rough) and pure tone phases of the stimulus produces different perceptions (indicated by horizontal bars). The interference of the modulation signals results in the supression and amplification of the modulation strength and has a frequency equal to 2 Hz beat frequency. The LFR follows the rhythm of these changes. Be-

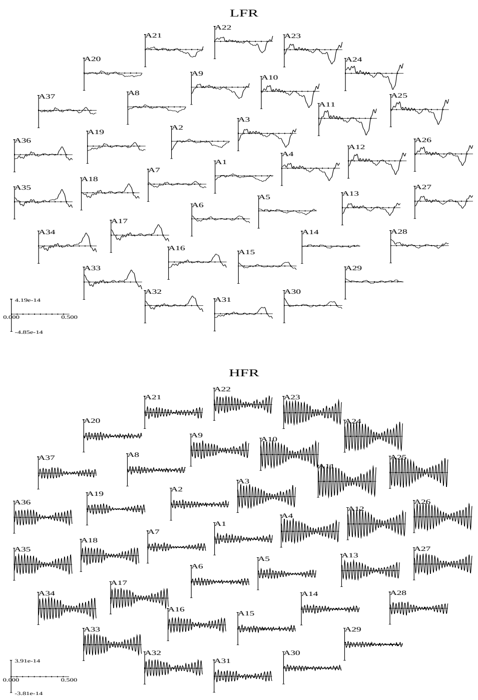

Figure 3: *Timeseries separated into two frequency bands, from 1 to 20 Hz (LFR, slow auditory evoked field) and from 20 to 100 HZ (HFR, steady-state auditory evoked field).*

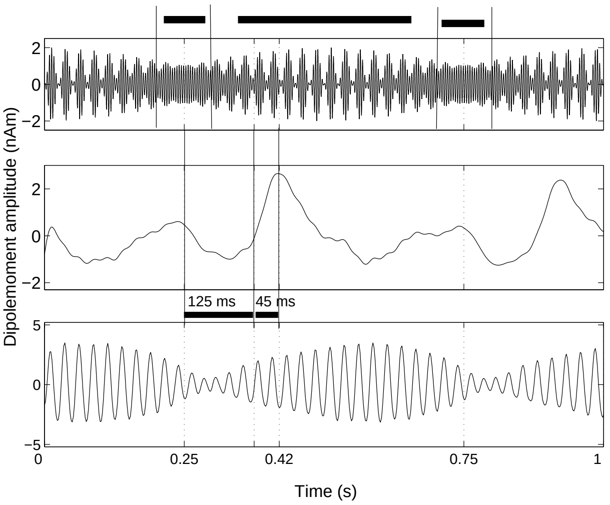

Figure 4: *Waveforms of stimulus (top) and of response signal filtered in low (LFR) and high (HFR) frequency band.*

cause of the missing trigger determining the stimulus onset, a relative trigger was assumed, placed at the first amplitude minimum of the 2 Hz stimulus envelope at 0.25 s. A time interval of 125 ms after this time point was necessary for reaching the mean value of the envelope amplitude. We have assumed that at this instant, the stimulus intensity is able to evoke an auditory response. Indeed, a pronounced wave of the LFR was observed about 45-50 ms after this time instant. Another wave with a smaller amplitude was observed after decreasing of the stimulus intensity, at the minimum of the envelope amplitude.
The HFR contains spindles of the modulation frequencies of 38 and 40 Hz. The response strongly resembles the time structure of the stimulus following the amplitude fluctuation of its envelope.

4 Discussion

4.1 Low frequency response (LFR)

Most of the referenced studies were concerned with the modulation frequencies of the rate producing perceptions of roughness and pitch. A little attention has been paid to slow rhythmically changes of amplitude, resulting in the hearing sensation "fluctuation strength" (below 20 Hz). It is already demonstrated in MEG studies [7], that this response (between 10 and 20 Hz) is characterised by waveforms periodically repeated in time, forming patterns, phase-locked to the stimulus envelope. Our study demonstrates a time structure of the response corresponding to slow rhythmic changes between modulated and pure tone phases of a multiple modulated stimulus, eliciting different perceptions. Characteristic for the LFR is the similarity of the obtained pattern with those of the components of the transient evoked response P1-N1-P2. This result is related to this of a previous study [5], demonstrating the ability of the auditory cortex to respond to pairs of intermittent AM tones with transient pattern. Therefore, we compared the polarity of the major component of our LFR and the classical N1 component, and found that the two responses are of opposite polarity. The positive polarity of the major component in LFR suggests rather similarity with the transient P1 or P2 components. However, its latency of about 45-50 ms, as described in the results, corresponds to the latency of P1 component. This fact leads to the hypothesis of relationship between the major LFR component and the P1. Therefore, it can be concluded that the auditory system possess the ability to perceive and process slow temporal changes in a complex amplitude modulated auditory signal. It is a new finding, that the rhythm of these changes is coded in the auditory cortex as periodically repeated slow positive wave, similar to the P1 component.

4.2 High frequency response (HFR)

In contrast, the frequency spectrum of the SSR demonstrates the ability of the auditory system to detect and respond to the modulation frequencies of the stimulus. The peaks at both modulation frequencies at 38 and 40 Hz are in agreement with previous studies [2, 4]. These studies investigated responses to multiple modulated tones and analysed only the aspects of their spectral characteristic amplitude and phase.

Previous studies in humans [3], demonstrated that the auditory cortex is able to respond to an AM stimulus following the stimulus envelope, i.e. the fluctuation of the modulation frequency amplitude. Ross et al. [7] have described the time-course of the source wave form of the SSR evoked by an AM stimulus and demonstrated, for frequencies between 30 and 80 Hz that the response strongly follow the sinusoidal shape of the modulation frequency. In our study we have demonstrated the temporal structure of such a response within the frequency modulation range of 40 Hz, generating roughness perception. Amplitude modulation at 38 and 40 Hz is perceived as roughness and elicits SSR at both modulation frequencies 38 and 40 Hz. However, the response signal also contains the interference between both modulation frequencies.

In conclusion, it can be hypothesized that the described stimulation, recording and analysis procedure may allow to study speech disorders and central auditory disturbances due to neurological diseases.

Acknowledgments

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